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The Effect of Clustering on the Uncertainty of Differential Reflectivity Measurements

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ABSTRACT

One of the most important avenues of recent meteorological radar research is the application of polarization techniques to improve radar rainfall estimation. A keystone in many of these methods is the so-called differential reflectivity $Z_{DR}$, the ratio of the reflectivity factor $Z_H$ at horizontal polarization backscattered from a horizontally polarized transmission to that corresponding to a vertically polarized transmission $Z_V$. For such quantitative applications, it is important to understand the statistical accuracy of observations of $Z_{DR}$. The underlying assumption of all past estimations of meteorological radar uncertainties is that the signals obey Rayleigh statistics. It is now evident, however, that as a radar scans, the meteorological conditions no longer always satisfy the requirements for Rayleigh statistics. In this work, $Z_{DR}$ is reconsidered, but this time within the new framework of non-Rayleigh signal statistics. Using Monte Carlo experiments, it is found that clustering of the scatterers multiplies the standard deviation of $Z_{DR}$ beyond what is always calculated assuming Rayleigh statistics. The magnitude of this enhancement depends on the magnitudes of the clustering index and of the cross correlation between $Z_H$ and $Z_V$. Also, it does not depend upon the number of independent samples in an ensemble estimate. An example using real radar data in convective showers suggests that non-Rayleigh signal statistics should be taken into account in future implementations of polarization radar rainfall estimation techniques using $Z_{DR}$. At the very least, it is time to begin to document the prevalence and magnitude of the clustering index in a wide variety of meteorological conditions.

1. Introduction

For over 25 years, the applications of radar polarization measurements have been thoroughly explored by a multitude of investigators. One of the most important avenues of research has been that directed toward improving radar rainfall estimation. A keystone of many of these methods is the so-called differential reflectivity, the ratio of the reflectivity factor $Z_H$ backscattered at horizontal polarization from a horizontally polarized transmission to that corresponding to a vertically polarized transmission $Z_V$. Indeed, it now appears that $Z_{DR} = Z_H/Z_V$ is destined to play an increasingly important operational role when polarization technology is added to current and future national meteorological radar systems.

It is important, then, to understand the measurement accuracy of $Z_{DR}$, usually expressed in terms of the standard deviation. Consequently, it is not surprising that the signal statistics of $Z_{DR}$ have been thoroughly treated in past studies beginning with Bringi et al. (1983). Recently, however, some investigators (Gorgucci et al. 2006, p. 3039) even claim “typical” accuracies of 0.2 dB (about 5%). While that would be wonderful if true, this work shows why that degree of accuracy is often unlikely, in reality. It is important, then, not to oversell the anticipated accuracy of some polarization rainfall estimation techniques that are likely to be implemented in future national meteorological radar systems, particularly in light of the inherent variability of the rainfall rate itself (Jameson 2008).

The underlying assumption of all past studies is that the signals obey Rayleigh statistics (Rayleigh 1877) as
reexpressed for radar meteorology by Marshall and Hitschfeld (1953). The derivation of Rayleigh statistics assumes that all waves from each particle scatter independently and that conditions are statistically stationary (or equivalently, spatially homogeneous). Thus, at any location, the net observed wave is then the sum of all the independent waves having randomly distributed phases.

Rather than directly measuring the amplitude and phase of the net wave, for radars it is more convenient to measure the so-called real $\mathcal{R}$ and imaginary $\mathcal{Q}$ orthogonal components. These can be thought of as the $x$ and $y$ axis projections, respectively, of a complex phasor (vector) rooted at an axis origin that has a magnitude equal to the amplitude of the net wave and an angular position around a circle given by the phase. From this perspective, Rayleigh statistics implies that the $\mathcal{R}$ and $\mathcal{Q}$ components are Gaussian distributed and are statistically independent. The statistical distributions of the amplitude (the Rayleigh distribution) and intensities (exponential distribution) can then be readily calculated.

As Marshall and Hitschfeld demonstrated, this approach is useful for a basic understanding of radar signals at one polarization or frequency. They also showed that mean intensity calculated from $k$ statistically independent samples could then be written as an Erlang distribution having a shape dependent on $k$. The larger the $k$, the narrower and more Gaussian-like the distribution of the mean values. While as important as these findings are, there are situations when they do not apply.

For example, there have been past measurements suggesting that, at times, the statistics may deviate from Rayleigh (e.g., Schaffner et al. 1980). Unfortunately, the origins of the signals were not completely understood, leading most observers to conclude that such deviations were “unusual” and not a challenge to the predominance of Rayleigh statistics. We return to this in a moment.

While most radar measurements involve only one parameter, the complicated nature of meteorological conditions has forced increasing sophistication. For example, for some purposes it is often useful to measure two parameters that, when combined, yield greater information. One example is dual-wavelength hail detection involving the ratio of two radar reflectivity factors measured at two different frequencies. Such ratios present a statistical problem especially when they involve variables with probability density functions (pdfs) having extended tails. In the case of dual-wavelength hail detection, the statistics were first considered by Srivastava and Carbone (1971). Since the samples at the two frequencies are entirely statistically independent, the statistics of the dual-wavelength ratio is then the ratio of two Erlang distributions, which, it turns out, is a beta distribution, as shown in many texts on statistics. That distribution is usually asymmetric, often having quite extended tails that seriously challenge the statistical reliability of such measurements.

Indeed, if $Z_H$ and $Z_V$ were completely statistically independent, $Z_{DR}$ would also be beta distributed, having long, extended tails, thereby seriously compromising the usefulness of $Z_{DR}$. This can be understood by simply realizing that when the two signals are statistically independent, a small value of $Z_V$ might occur simultaneously with a large value of $Z_H$ so that $Z_{DR}$ could, at times, reach tremendous values. This would not necessarily be an infrequent event either. Fortunately, in precipitation, $Z_H$ and $Z_V$ are usually highly correlated ($\rho_{HV} \sim >0.98$). This correlation severely restricts the range of values of $Z_{DR}$. That is, large $Z_H$ and $Z_V$ as well as small $Z_H$ and $Z_V$ will occur simultaneously so that their ratio remains close to the expected value regardless of extreme fluctuations in either quantity. Consequently, Bringi et al. (1983) and subsequent studies all treat $Z_{DR}$ as the ratio of two highly correlated quantities, each consistent with Rayleigh signal statistics.

Letting $\langle \rangle$ denote an ensemble average and $E$ the expected value, the normalized differential reflectivity can be expressed as $X = \langle (Z_H)/(Z_V) \rangle/\langle E(Z_H)/E(Z_V) \rangle$. Using Eq. (3) in Bringi et al. (1983) and changing the variables from normalized amplitudes to normalized differential reflectivities, the pdf is given by

$$P(X) = \frac{(1 + X)(1 - \rho_{HV})}{[(1 + X)^2 - 4\rho_{HV}X]^{3/2}},$$

where $\rho_{HV}$ is the cross polarization between the backscattered intensities at the two polarizations. While this distribution exists and integrates to unity over $[0, \infty]$, and while there is a modal (expected) value, the mean and variance (or any other moment) do not exist because the tail of the distribution goes as $1/X^2$ (Fig. 1), as can be derived from (1) for large $X$, so that the moments do not converge. Bringi et al. (1983) circumvent this peculiarity by considering, instead, the statistics of an estimator of the expected value that comes from the summation of the Gaussian $\mathcal{R}$ and $\mathcal{Q}$ components at the two polarizations. The resulting statistics can then be treated using the analyses of Krishnaiah et al. (1963) for correlated bivariate chi distributed variables which arise from such summations. The Cramer–Rao lowest possible bound to the variance of $Z_{DR}$ for such circular
Gaussian models can also be computed (Schultz and Kostinski 1997). As useful as these results have been, however, it is becoming increasingly evident that, as a radar scans, conditions are not statistically stationary often in important meteorological settings. Rather, most precipitation is statistically heterogeneous so that radar signals do not satisfy the conditions required for Rayleigh statistics (Jameson and Kostinski 1996; Jameson 2008). That is, non-Rayleigh signal statistics are likely not as rare as previously assumed. Even in situations of statistical homogeneity, conditions may fluctuate significantly largely because of the spatial clustering of the scatterers [for a discussion see Kostinski and Jameson (1997) and Jameson and Kostinski (2000)]. When that is the case, the central limit theorem, required to produce Rayleigh statistics, is violated (Jameson and Kostinski 1996, 1999).

In light of this, it is reasonable to return to a reconsideration of the statistics of $Z_{DR}$ but this time within the new framework of non-Rayleigh signal statistics. While the theoretical calculations performed here are for statistically homogeneous situations, we do consider some real data as well. Consequently, since real data is usually likely statistically heterogeneous, we also consider those cases when the statistical heterogeneity are consistent with the description of Jameson (2007). As argued in appendix A, even in such statistically heterogeneous cases, the statistics of the fluctuations (the standard deviation), are largely (i.e., about 80%-100% as discussed in appendix A) determined by clustering.

So how can we compare cases when clustering is absent with those when it is present? First of all, as just noted, the variance cannot be used since it does not exist for (1). Nor can we use the theoretical approach of Bringi et al. (1983) using the statistics of an estimator since the $R$ and $Q$ components are no longer Gaussian when there is clustering (shown below). This means that, unlike for Rayleigh statistics, a closed-form analytic solution corresponding to non-Rayleigh statistics is not possible. Instead, we must turn to Monte Carlo calculations as discussed in section 3 and in appendix B. Like Bringi et al. (1983) we then average over a certain number of samples of the intensities at the two polarizations to estimate $Z_{DR}$. We then compute the standard deviation and compare it to the Rayleigh standard deviation given by (7) in Bringi et al. (1983). As shown later, this ratio of the clustered to Rayleigh standard deviation does not depend upon the number of independent samples used to calculate an estimate of $Z_{DR}$. However, before doing all of this, we first briefly review clustering and present a framework used in subsequent calculations.

2. On the distribution of intensities in a clustered environment and the role of statistical heterogeneity

A detailed discussion of one derivation of the distribution of radar intensities in a clustered environment may be found in Jameson (2005). Here, the relevant points are presented with regard to this paper before proceeding with the calculations. (Some further discussions relevant to the interpretation of actual measurements in statistically heterogeneous conditions are given in appendix A with an example presented in section 4.)

The spatial variability of precipitation is widely acknowledged. How does this affect radar observations? Radars measure the reflectivity factor ($Z$) derived from observations of backscattered intensities ($I$) in sample volumes. For stationary antennas, the signal fluctuations are determined by random coherent summations of the electromagnetic waves reflected by the individual particles as described by Rayleigh statistics. The variance then equals the mean squared (i.e., the relative dispersion of the intensity, $\sigma_I/I$, is unity for the exponential distribution of intensities arising from Rayleigh statistics). For scanning antennas, however, additional deviations occur as clustering and statistical heterogeneities extend the tail of the distributions of the relative dispersion.
That is, Rayleigh statistics are based upon the central limit theorem applied to each of the two components of the complex amplitude when conditions are “near” statistical stationarity. Jameson and Kostinski (1996) explored the meaning of near stationarity and concluded, for the simple case of drops of one size, that whenever the number of drops within the beam fluctuated from sample to sample by more than about 15% of the mean, non-Rayleigh effects could be detected. Why? Because now the measurement not only depends upon the constructive and destructive interference of the waves scattered off all the drops, it also depends upon the doubly stochastic nature of the process in which the number of scatterers themselves becomes a random variable largely because of the motion of the observation volume between successive radar samples. [A more complete discussion of the origin of non-Rayleigh signal statistics may be found in Jameson and Kostinski (1996).] What causes the number of drops to vary?

A central source of drop concentration fluctuations in a moving radar sample volume is clustering, which is the enhanced concentration (and dilution) of particles associated with increased (decreased) correlations of scatterers in neighboring volumes. That is, the number of drops in neighboring volumes is not statistically independent.

An important variable for quantitatively describing the clustering is the clustering index $CI$, defined by

$$\text{CI} = \frac{\delta N^2}{\bar{N}^2} - \frac{1}{\bar{N}},$$

where $\bar{N}$ and $\delta N^2$ are the mean and variance of the number of scatterers from sample volume to sample volume members of an ensemble of such samples. Thus, when there is no clustering, $\delta N^2 = \bar{N}$ and $\text{CI} \to 0$. Because the clustering intensity goes as $\delta N^2/\bar{N}^2 - 1/\bar{N}$, the second term often quickly becomes negligible for most realistic radar sample volumes so that $\text{CI} \to (\delta N^2/\bar{N}^2)$.

As previously mentioned, another source of drop concentration variability is statistical heterogeneity, the result of changing conditions such that the statistics of the observations depend upon the location of the measurements. Consequently, radar intensity measurements exhibit increased variance (and relative dispersion) because of the bunching of drops produced by correlation (i.e., clustering) and because of systematic changes in the observed longer-term or larger-scale mean values of drop concentrations associated with statistical heterogeneity. As antennas scan during sampling, then, radars “see” the effects of all of this variability (clustering in conjunction with heterogeneity) in addition to the usual Rayleigh signal coherency fluctuations.

As the absence of any discussion in statistics textbooks indicates, the subject of statistical heterogeneity has been a difficult problem to address particularly with any generality. Recently, however, Jameson (2007) showed that statistically heterogeneous rain can apparently be decomposed into a half dozen or so statistically homogeneous components (i.e., steady drop size distributions). The statistically heterogeneous rain event, then, can be described (and, indeed, reconstituted) using linear, weighted combinations of these different statistically homogeneous components. In so far as these results are generally applicable, it then provides insight into our meteorological interpretation of non-Rayleigh signal measurements in statistically heterogeneous conditions. Using the conservative estimate discussed in appendix A and expression (A8) in Jameson (2008), it is found that

$$\frac{\sigma^2(Z)}{E^2(Z)} = \frac{5}{4} \sum_i \frac{w_i E_i(Z)^2}{\langle E(Z) \rangle^2} = \frac{5}{4} \sum_i \frac{w_i E_i(Z)}{\langle E(Z) \rangle}^2,$$

(3)

where $E$ denotes the expected value, $w_i$ are the weighting functions corresponding to each of the statistically homogeneous components, $\langle \cdot \rangle$ denotes an ensemble average, and the “overbar” denotes a weighted average.

Thus, the squared relative dispersion of $Z$ is determined by the summation over the clustering indices for each statistically homogeneous component of the statistically heterogeneous rain multiplied by the square of the fractional contribution each component mean $E_i(Z)$ makes to the overall average $Z$ times a factor. Hence, one may think of the second multiplicative term as weighting factors representing the effect of statistical heterogeneities. Thus, for most radar measurements we conclude that in statistically heterogeneous rain 80%–100% of $\sigma^2(Z)/E^2(Z)$ provides a measure of a weighted average clustering index, while in statistically homogeneous rain the relative dispersion of $Z$ provides a direct estimate of the clustering index.

It is also important to note that in (3), $Z$ is the intrinsic radar reflectivity factor (without signal fluctuations) and not the measured $Z$. Since Rayleigh signal coherency fluctuations are present in actual observations, it is shown in Jameson (2008) that the observed and intrinsic relative dispersions are related by

$$\frac{\sigma^2(Z)}{E^2(Z)}_{\text{Observed}} = \frac{\sigma^2(Z)}{E^2(Z)}_{\text{Intrinsic}} + 1 = \text{CI} + 1,$$

(4)
where unity appears because of the presence of Rayleigh signal fluctuations. Moreover, when there are a sufficient number of statistically independent samples, CI can then be reliably extracted from observations (Jameson 2008) by first subtracting unity from the measured $\frac{\sigma^2}{\mathcal{Z}^2}$ and then multiplying by a factor between 80%–100%.

3. Results from Monte Carlo simulations of signal statistics in a clustered environment

In this section we first sketch out the procedure and then discuss some results. First, a random, uncorrelated 10 million element time series is generated for the BesselK distribution (Jameson 2005) for CI = 2, 4, and 6 over the range $0 \leq I/I_0 \leq 200$ as discussed in appendix B. An example of the simulated frequency distribution is compared with theory in Fig. 2. Clearly, the simulations work quite well. The difference between the Rayleigh statistics (CI = 0) exponential distribution and the clustered non-Rayleigh statistics is strikingly apparent. The long tails of the clustered distributions indicate that the standard deviations of the intensities should be significantly enhanced beyond that for the Rayleigh exponential distribution of intensities. One initially suspects, then, that this could potentially have an effect on the variance of the differential reflectivity.

To explore this, we next generate a pair of correlated time series of BesselK distributed intensities, one for horizontal and one for vertical polarizations having a $\rho_{HV}$ ranging from approximately 0.2 to 0.995. These correlated intensity time series can be used in two ways. First, Fig. 2 suggests that the distributions of complex amplitude component, $\mathcal{R}$ and $\mathcal{Q}$, may no longer be Gaussian. Indeed, this is the case as Fig. 3a confirms. The distribution is definitely non-Gaussian with tails that far exceed those for the normal distribution for the same mean intensity. While somewhat like a Lorentz distribution in appearance, a closer inspection (not shown) reveals that the distribution actually has longer
and more significant tails than does a Lorentz pdf. In fact, it can be shown that, for the BesselK distribution of intensities, the distribution for the \( Q \) component is given by

\[
P(Q) = \frac{2}{\pi t^2} \left( \frac{1}{B^2} \right)^{1/4} \left( 1 + 2/C \right) \left( \frac{1}{Q^2} \right)^{1/4} \left( 1 - 2/C \right) BesselK \left[ \frac{1}{C} \right],
\]

where \( C \) is the clustering index, BesselK is the modified Bessel function of the first kind,

\[
B = \frac{\text{rms}(Q)}{\sqrt{(C^2 + C)}},
\]

and \text{rms} denotes the root-mean-square. The same distribution also holds for \( R \). Such distributions (Fig. 3a) appear in observations as well (Fig. 3b), giving us some confidence in this approach.

Second, the statistics of \( Z_{\text{DR}} \) can then be calculated. Figure 4 shows an observed distribution of \( Z_{\text{DR}} \) compared to the appropriate distributions assuming Rayleigh and clustering statistics. These data are from dual-polarization time series measurements of the \( R \) and \( Q \) components at alternating polarizations from a stationary antenna over several seconds yielding around 80,000 independent samples over the same locations. Non-Rayleigh effects are then observed by combining observations along the beam. This is analogous to looking at data from a single range bin as it scans rapidly multiple times through the same set of heterogeneous conditions. Here the parameter \( X \) is the ensemble observed value normalized by the expected \( Z_{\text{DR}} \), as defined previously. The difference between these two frequency distributions of \( X \) for the measured \( \rho_{\text{HV}} = 0.970 \) are fairly typical. We note the broadening of the distribution in the clustered environment as compared to that corresponding to Rayleigh statistics (\( C = 0 \)). The likely source of this enhanced broadening is the extended tails of \( R \) and \( Q \) (Fig. 3) as exhibited by the extended tails of the intensity distribution (Fig. 2). As with the Rayleigh statistics, \( \rho_{\text{HV}} \) acts to significantly reduce the spread in the distribution of \( Z_{\text{DR}} \), but in the clustered environment, that is still insufficient to return the variance of \( Z_{\text{DR}} \) to Rayleigh values.

Now in Fig. 4, there is no averaging; that is, the curves are the frequency distributions of statistically independent pulse to pulse values of \( X \). In reality something like 5–10 independent samples will provide an ensemble average so that both distributions in Fig. 4 would be narrower. Regardless, however, what is important is that the standard deviation in the clustered environment will always be greater than the value computed assuming Rayleigh statistics. This is illustrated in greater detail in Fig. 5.
of independent samples \( m \). This occurs because both \( \sigma_{\text{Clustered}} \) and \( \sigma_{\text{Rayleigh}} \) essentially depend on the number of independent samples in the estimate as \( 1/\sqrt{m} \) (Fig. 6a) so that the ratio of the clustered to Rayleigh standard deviations are independent of \( m \) (Fig. 6b). Thus, for example, if one calculates that \( \sigma_{\text{ZDR}} \approx 0.2 \) dB, (or 1.047 on a linear scale) as Gorgucci et al. (2006) suggest, the standard deviation may actually be, say, 0.4 dB (1.097) to 1.2 dB (1.230) or larger depending upon CI and \( \rho_{\text{HV}} \) at the location of the observation.

The objective of this work, then, is simply to suggest using reasonable caution by pointing out the potential effect of clustering on measurements of \( Z_{\text{DR}} \) and to...
leave any rational scientist at least thinking about just how much such clustering may affect the future operational accuracy of some polarization rainfall algorithms. At the very least, values as low as Gorgucci et al. (2006) suggest seem highly improbable much of the time as illustrated later in Fig. 7 except, perhaps, in less interesting meteorological conditions.

However, with our current nearly nonexistent measurements of the clustering index it is impossible to generalize the extent of the effect of clustering on radar measurements except to note that, regardless of radars, clustering appears to be ubiquitous throughout most precipitation. When and where that will be significant remains to be determined through extensive observations. However, in the next section, one example from a rare set of observations of CI is presented. While its relevance should not be viewed with any sweeping generality, of course, it does raise valid concerns and suggests the importance of gathering further observations of the clustering index in a number of different meteorological settings.

4. A sample observation

The azimuthal-range scan considered in this section was measured on 9 September 2005. Details may be found in Jameson (2008), but some of the relevant information is repeated here as well. These data were kindly provided by Dave Brunkow of the University of Chicago–Illinois State Water Survey (CHILL) National Radar Facility at Colorado State University in Fort Collins, Colorado. In both cases the observations were made in rain by the CHILL radar that has a nominal 1° beam and wavelength of 10 cm.

In each scan, over a set of 150-m range bins and over several degrees of azimuth, the $R$ and $Q$ data were given for each pulse. This permitted a detailed inspection of data quality (e.g., the $R$ and $Q$ were found to be completely balanced). It was also then possible to compute the intensity ($R^2 + Q^2$) for each pulse and range bin. Data over a number of pulses and range bins were then used to estimate the variance and mean of $I$ and, therefore, the variance as discussed in appendix A and the text. The number of data bins combined was selected to preserve as high a spatial resolution as possible while still yielding a reasonable number of statistically independent samples. The number of statistically independent samples was estimated assuming that there were 5 independent samples per 1° of azimuth and that the range bins along each azimuthal radial separated by 1° were also statistically independent. This means that the estimate of the number of independent samples for each estimate of the variance and mean of $I$ were, on average, on the order of 13 in this example. As explained in Jameson (2008), the corresponding 99% confidence threshold that the observed relative dispersions (squared) of $Z_H$ were not Rayleigh in origin was found to be 2.24 (i.e., a CI of 1.24). That is, any CI greater than 1.24 were 99% likely not due to Rayleigh fluctuations, or to put it more positively, they were 99% likely due to clustering (weighted by statistical heterogeneity, of course).

To see where clustering is occurring, the shaded contours of radar reflectivity $Z_H$ are shown in Fig. 7a
adapted from Jameson (2008) along with the contours of the clustering index in unit steps beginning with the modest CI = 1.3. In this example, the most significant values of the clustering index are often found in or near the highest radar reflectivity factors such as in the core of a small, convective shower at about 156° azimuth and 36-km range (156°, 36 km). This need not always be the case, however (Fig. 5 of Jameson 2008).

To get an idea of what this means with respect to the level of uncertainty in \( Z_{\text{DR}} \) we assume that \( \rho_{\text{HV}} = 0.98 \). From the numbers used to generate Fig. 5, it is found that the ratio of \( \sigma_{\text{Clustered}}/\sigma_{\text{Rayleigh}} \) goes as \( (1.00 + 1.083\text{CI})^{1/2} \) at this \( \rho_{\text{HV}} \). Using this expression, the clustering indices are converted into the ratio of the standard deviations. These are plotted in Fig. 7b in steps of 0.2 beginning at 1.2. Clearly, there are areas over which the uncertainty is significantly greater than Rayleigh statistics would imply. So, for example, near the core of the shower in Fig. 7, one would have to multiply \( \sigma_{\text{Rayleigh}} \) by a factor of more than 2.8, yielding an uncertainty of almost 1 dB if the estimated uncertainty based on a Rayleigh assumption had been 0.4 dB. Thus, in this case the uncertainty is greatest just where accurate estimates of, say, the rainfall rate are most desirable, namely near the core of the most intense shower.

5. Summary and conclusions

Polarization measurements are poised to play an increasingly important role in future operational radar systems. While polarization observations can contribute in many ways, one of the most quantitative applications will be to radar rainfall measurement. In particular, many studies have suggested that polarization rainfall estimates, for example, can significantly improve such estimates relative to those derived using the standard radar reflectivity–rainfall rate \((Z-R)\) relations in current use.

A key parameter in all of these polarization–rainfall algorithms is the differential reflectivity \((Z_{\text{DR}})\), the ratio of the radar reflectivity factor measured using horizontally polarized waves to that observed using vertical polarization \((Z_{\text{HV}}/Z_{\text{V}})\). As with any scientific variable, it is important to understand the statistics associated with \( Z_{\text{DR}} \). This was first addressed extensively by Bringi et al. (1983) and in subsequent studies under the assumption that Rayleigh signal statistics, as expounded for radar by Marshall and Hitschfeld (1953), apply. This has been the solitary approach to radar signal statistics since the beginning days of radar meteorology.

Rayleigh statistics, however, are based upon two essential assumptions, namely that conditions are statistically stationary during sampling and that each particle scatters independently. It is becoming increasingly evident, however, that as a radar scans and in important meteorological settings, conditions are not statistically stationary in time (i.e., they are statistically heterogeneous across the sampling space) so that often, radar signals do not satisfy the conditions required for Rayleigh statistics (Jameson 2008). Even in those rare situations of statistical homogeneity, conditions may fluctuate significantly largely because of clustering or bunching of the scatterers (Kostinski and Jameson 1997; Jameson and Kostinski 2000) so that the central limit theorem, required to produce Rayleigh statistics, is violated (Jameson and Kostinski 1996, 1999). Since it appears meteorologically that the clustering of particles is nearly ubiquitous, non-Rayleigh signal statistics can no longer be attributed to unusual meteorological conditions.

Therefore, in this study we return to a reconsideration of the statistics of \( Z_{\text{DR}} \) but this time within the new framework of non-Rayleigh signal statistics. Here, as discussed in the text [and in so far as the results in Jameson (2007) apply], even in conditions of statistical heterogeneity, clustering is largely responsible for the statistics of the fluctuations (see appendix A and Figs. 4 and 5), although other terms due to statistical heterogeneity may also contribute at times (appendix A). Consequently, as has been done in all previous studies, in the theoretical analysis we consider only statistically homogeneous but clustered conditions remembering that our conclusions are likely applicable in a substantial degree to those statistically heterogeneous cases consistent with the results in Jameson (2007) as argued in appendix A.

For reasons given in Jameson (2005), the BesselK function is used as the probability density function (pdf) of radar intensity measurements in a clustered environment. This has the advantage that the clustering index is explicit in the intensity distribution. However, because of the correlation, \( \rho_{\text{HV}} \), between \( Z_{\text{HV}} \) and \( Z_{\text{V}} \), a direct analytic solution for the statistics of \( Z_{\text{DR}} \) is not possible so that Monte Carlo calculations (appendix B) are used to study the effect of clustering on the standard deviation of \( Z_{\text{DR}} \) using the estimator of averaged powers [Bringi et al. 1983, their Eq. (4)].

It is found that \( \sigma_{Z_{\text{DR}}} \) is significantly enhanced by clustering to a degree that depends upon the clustering index and \( \rho_{\text{HV}} \). It is noteworthy, however, that, regardless of how small the Rayleigh standard deviation is reduced by increasing the number of independent samples \( m \), clustering still magnifies that Rayleigh standard deviation by an amount that is independent of \( m \). This effect is present even for \( \rho_{\text{HV}} \) approaching unity.
and over the range of CI values likely to be found in most real observations.

As pointed out in Jameson (2008), most current radar observations of reflectivity factors alone are unlikely to be too affected by non-Rayleigh signal statistics because of the small number of independent samples used to form estimates. However, that is not the case for more sophisticated observations such as the differential reflectivity involving ratios of such parameters as Fig. 6 demonstrates. All current observations of $Z_{DR}$ are likely affected to varying degrees. Using the methodology described here and in Jameson (2008), an example in convective showers suggests that this amplification of $\sigma_{Z_{DR}}$ by non-Rayleigh signals should be taken into account in future implementations of polarization radar rainfall estimation algorithms. At the very least, it is time to begin to document the prevalence and magnitude of clustering and its subsequent generation of non-Rayleigh signal statistics in a wide variety of meteorological settings if we are going to embrace with confidence more quantitative applications of radar observations.

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APPENDIX A

On the Contribution of Clustering to the Relative Dispersion of the Radar Reflectivity Factor in Statistically Heterogeneous Environments

In previous work (Jameson 2008) the relationship between the relative dispersion of the radar reflectivity factor and the clustering index in a statistically heterogeneous environment was developed under the assumption that the weighting functions of the statistically homogeneous components of the heterogeneous data were represented by a Dirac distribution. Although nothing is yet known about those distributions, it seems likely that they will usually have some breadth expressed as a variance. It is shown below that when that is the case the variance (and, hence, the relative dispersion) of the radar reflectivity factor is enhanced by factors other than just the clustering, although that remains the predominant influence.

Specifically, we imagine an entire set of data having associated sets of weighting functions $\{w_i\}$ and realizations of $M$ components of the radar reflectivity factors $\{Z_i\}$. For one realization from this ensemble of observations $Z' = \sum_{i=1}^{M} w_i Z_i$ it then follows that

$$Z = \langle Z' \rangle = \sum_{i=1}^{M} w_i Z_i = \sum_{i=1}^{M} \langle w_i \rangle Z_i = \sum_{i=1}^{M} w_i Z_i,$$

while

$$\overline{Z}^2 = \langle Z'^2 \rangle = \left\langle \left( \sum_{i=1}^{M} w_i Z_i \right)^2 \right\rangle = \sum_{i=1}^{M} w_i^2 Z_i^2 + \sum_{i \neq j} w_i w_j Z_i Z_j = \sum_{i=1}^{M} w_i^2 Z_i^2 + \sum_{i \neq j} w_i w_j Z_i Z_j,$$

so that

$$\sigma_Z^2 = \overline{Z}^2 - Z^2 = \sum_{i=1}^{M} \sigma_w^2 \sigma_{Z_i}^2 + \sum_{i=1}^{M} \sigma_w^2 Z_i^2 + \sum_{i \neq j} w_i w_j \sigma_{Z_i}^2 + \sum_{i \neq j} Z_i Z_j \text{cov}(w_i, w_j),$$

where it is assumed that the $Z_i$ are statistically independent. In contrast to the derivation in Jameson (2008) additional terms are now included to reflect the complete contribution from the statistical heterogeneity. This means that the observed relative dispersion of $Z$ will be enhanced beyond that due solely to clustering. Let us estimate by how much.

Give our current state of knowledge, it is now assumed that the $w_i$ are statistically independent so that (A3) becomes

$$\sigma_Z^2 = \overline{Z}^2 - Z^2 = \sum_{i=1}^{M} \sigma_{w_i}^2 \sigma_{Z_i}^2 + \sum_{i=1}^{M} \sigma_{w_i}^2 Z_i^2 + \sum_{i=1}^{M} w_i^2 \sigma_{Z_i}^2,$$

(A4)

Unfortunately, at present nothing is known about the pdf of $w$. Consistent with this ignorance, the assumption is also made that the distributions are uniform over $[0, 1]$ for all $w_i$. In that case $\sigma_{w_i}^2 = 1/3 w_i^2$ so that (A4) reduces to

$$\sigma_Z^2 = \overline{Z}^2 - Z^2 = \frac{1}{3} \sum_{i=1}^{M} w_i^2 Z_i^2 + \frac{4}{3} \sum_{i=1}^{M} w_i^2 \sigma_{Z_i}^2.$$  

Now, because of different meteorological conditions even within one set of observations, it is unlikely that the $Z_i$ are uniformly distributed. Since $Z_i^2$ is of the order $\sigma_{Z_i}^2$, to a reasonable approximation we can then write
Consequently, it is still expected that the clustering index will be a minimum of at least 60% of the intrinsic relative dispersion, and it seems far more likely (using more reasonable pdfs for $w_i$) that the minimum is more likely closer to 80%–100%. Furthermore, as the pdf of $w_i$ narrows, this percentage will increase until it is 100% for the Dirac distribution of $w_i$ as for the data in Figs. 4 and 5. However, to remain conservative, in this work it is assumed that the CI is represented by 80% of the intrinsic relative dispersion, realizing that in Fig. 7 that assumption may well be an underestimate.

APPENDIX B

The Monte Carlo Generation of the $R$, $Q$ Components and Correlated Intensities in a Clustered Environment

A random sequence of draws from the BesselK distribution of intensities corresponding to a clustering indices CI = 2, 4, and 6 are generated using the copula transformation method (Genest and Mackay 1986; Nelsen 1999; Frees and Valdez 1998) using correlated Gaussian distributions and a uniform random number generator (Fox et al. 1988). First, corresponding to a particular $\rho_{HV}$, two correlated time series of zero mean, Gaussian distributions with unit variance are generated. Using the inverse accumulated density function (CDF) for the Gaussian, these time series are then converted into correlated time series of uniformly distributed variables. Next, using the CDF of BesselK pdf, found through fitting procedures, one can generate an inverse function to transform the uniform random variables into BesselK random variables. The correlated intensities at both horizontal and vertical polarizations as well as $Z_{DR}$ can then be computed as illustrated in Fig. B1a.

Second, the $R$, $Q$ at both polarizations can also be computed by taking the square root of the just correlated intensities ($I_H$ and $I_V$) and then picking uniformly uncorrelated random phases ($\phi$) so that $R_{HV} = (A_H, A_V)\cos(\phi)$ and $Q = (A_H, A_V)\sin(\phi)$. Consequently, the random phases between $R$ and $Q$ are produced (Fig. B1b), while the intensities at the two polarizations remain correlated.

REFERENCES


